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Performance of harbour structures in Andaman Islands during 2004 Sumatra earthquake

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Abstract

The devastating M_w 9.1 Sumatra earthquake on 26 December 2004 and subsequent tsunami caused severe damages to harbour structures which caused delay in supply of relief work in the earthquake and tsunami affected areas in Andaman Islands, India. Major structural damage was observed at the construction joints due to pounding of two portions of jetties and at the top of reinforced concrete piles, especially short piles. Inadequate structural design and reinforcement detailing along with poor maintenance of these structures were primarily responsible for the severe damages. Other geotechnical aspects, e.g. liquefaction of soils, slope-stability failure, etc., were also responsible for severe damage to these structures. Appropriate seismic design provisions in applicable codes and their implementation are necessary to ensure satisfactory structural response for uninterrupted services at harbours in seismically active zones, especially those in developing countries.

Keywords: Sumatra earthquake; Andaman Islands; Harbour structures; Jetties; Pounding damage; Short-column effect; Liquefaction; Slope stability

1. Introduction

Wharves and jetties are lifeline structures as they provide a cost effective method for transporting large quantities of goods and raw materials into and out of a region. These harbour structures also play a significant role in the transportation system in terms of evacuation of people before and after natural disasters like earthquakes and tsunami. Further, these are useful to supply relief materials after a disaster when other transportation systems fail to deliver. Similar roles were accomplished by some of the less damaged ports and jetties in Andaman & Nicobar (A&N) Islands after 26 December 2004 when the great Sumatra earthquake of magnitude M_w 9.1 caused a devastating tsunami in the Indian Ocean. This earthquake occurred due to subduction of the Indian plate under the Burmese micro-plate and 283 106 people in the South and Southeast Asia died mainly due to subsequent tsunami [1]. The subduction zone was characterized by a NNW-SSE arcuate trench running parallel to the western side of Sumatra and the A&N Islands [2]. Apart from inundation due to the tsunami, intensive shaking was felt in Andaman Islands located about 1000 km north-west from the epicentre (03.295°N 95.982°E as per USGS, Fig. 1).

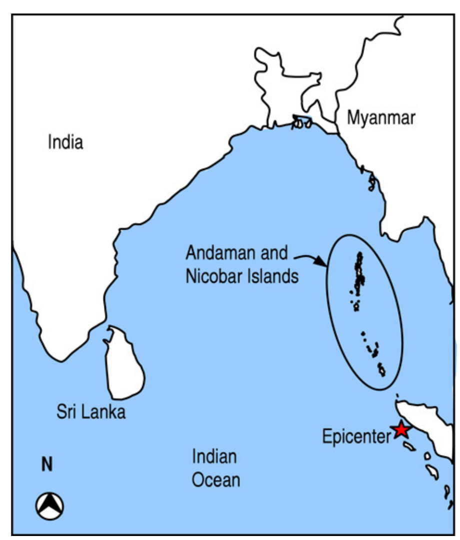

Fig. 1. Index map of Andaman and Nicobar Islands showing epicentre of the 2004 Sumatra earthquake.

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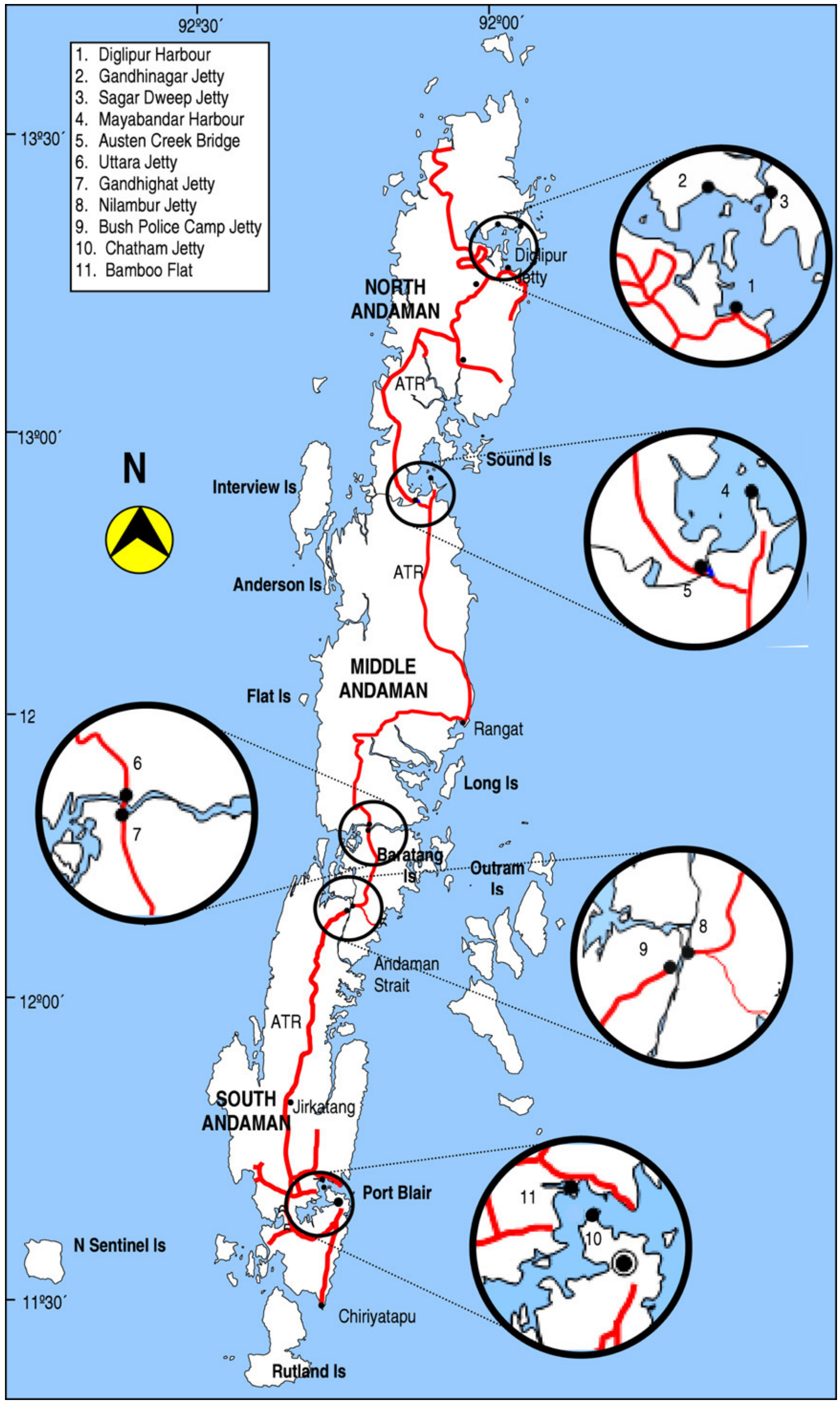

Fig. 2. Schematic diagram of Andaman Islands showing locations of harbours and jetties.

Andaman Islands consist of four major islands, namely Little Andaman, South Andaman, Middle Andaman and North Andaman, and several small islands, which are separated by creeks/straits. In the 2004 Sumatra earthquake, damage to jetties and surrounding offshore and foreshore structures inside the creek was primarily due to the earthquake shaking rather than the tsunami as they were shielded by small islands or protected by mangroves. However, the structures facing the open sea experienced damages due to tsunami. As per the Indian seismic hazard zone map [3], the entire A&N Islands lie in the most severe seismic zone, i.e. zone V, where the expected intensity of shaking is IX or greater on the MSK intensity scale. However, it was observed that the intensity of shaking in the 2004 Sumatra earthquake was between VI to VII [4]. Performance of the structures could have been better than what was observed if these had been designed and detailed properly.

Structural as well as geotechnical issues are the prime concern for harbour structures. Liquefaction, lateral spreading, slope stability, characterization of earth-fill for site response and soil–structure interaction are the main geotechnical issues

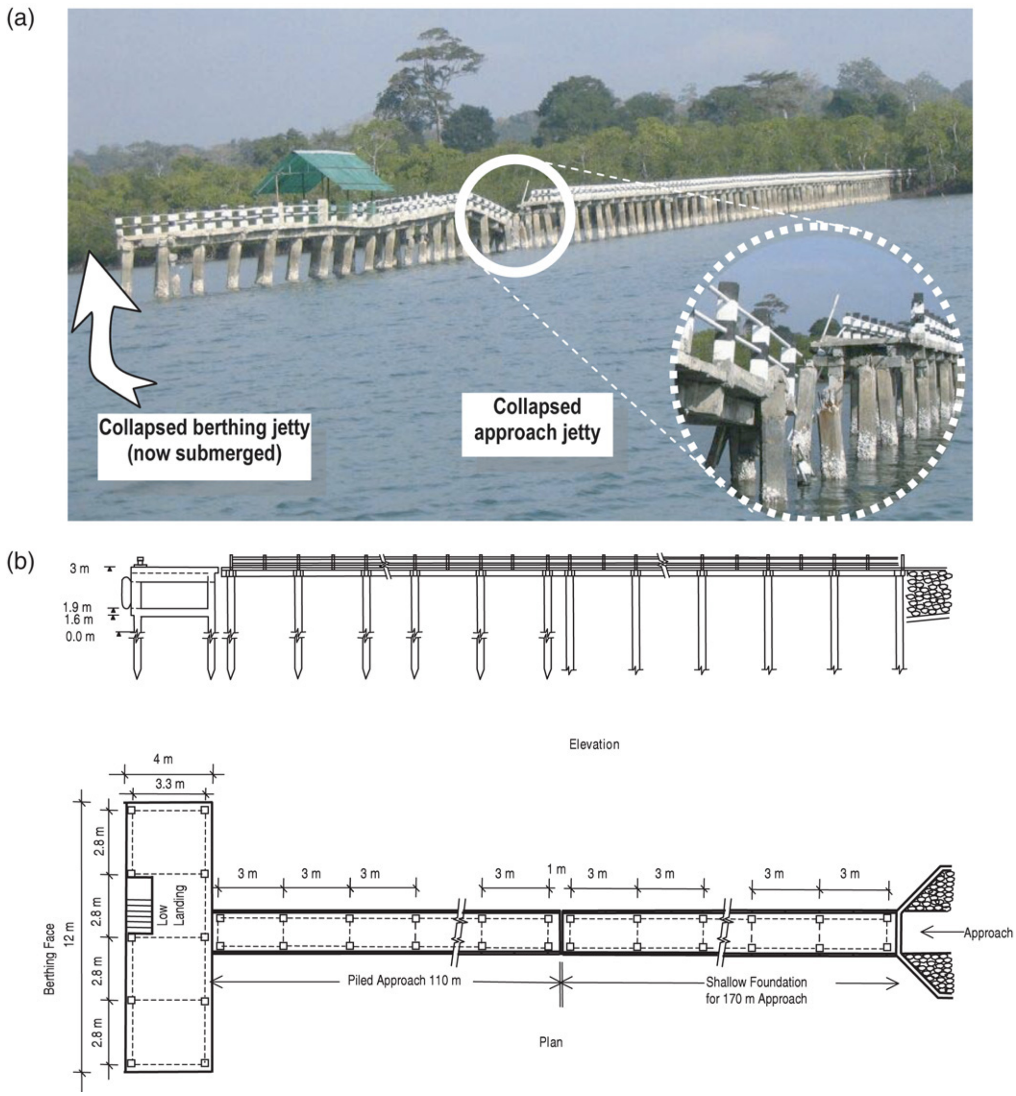

Fig. 3. Gandhinagar jetty in North Andaman: (a) Total collapse of the berthing jetty and partial collapse of the approach jetty, (b) Elevation and plan.

for harbour structures. In this paper geotechnical as well as structural damage along with remediation of such damage to different types of harbour structures, mainly, pile-supported jetty, breakwater, etc., at Andaman Islands are described.

2. Damage to pile-supported wharves

Jetties at Rangat Bay and Mayabandar Harbours in the Middle Andaman Islands, and at Diglipur, Sagar Dweep and Gandhinagar in the North Andaman Islands were severely affected, while Kalighat Jetty in North Andaman and Uttara Jetty in Middle Andaman sustained only minor damage (Fig. 2). Berthing jetty and a portion of approach jetty at Sagar Dweep totally collapsed during this earthquake/tsunami (Fig. 3).

Two types of piles are used in pile supported wharves and jetties in port structures, e.g. vertical pile and battered pile. In seismically active area, it is usual to design the pile-supported wharves and jetties with vertical piles only. Damage to these piles in bending is easy to restore as long as damage is concentrated at the pile head. On the other hand, a battered pile–deck system results in a much more rigid system than with vertical piles, and it responds to earthquakes by developing large axial compression or tension forces. Compression in piles results in material compression failure, buckling of piles, failure of pile–deck connection, etc. Therefore, special attention should be given to the application of batter piles.

During ground shaking, the response of pile-supported wharves is influenced by complex soil–structure interaction. Typical failure modes depend upon lateral displacement of the deck due to inertia force relative to the ground displacement (Fig. 4). Major features of observed damages of jetties or wharves along with their remedial measures can be described as in the following:

2.1. Pounding damages

Long jetties and piers are generally divided into segments by movement joints to accommodate thermal, creep and shrinkage movements. Generally, the joints allow free longitudinal movements and restrain transverse displacements during mooring and berthing operation. However, during an

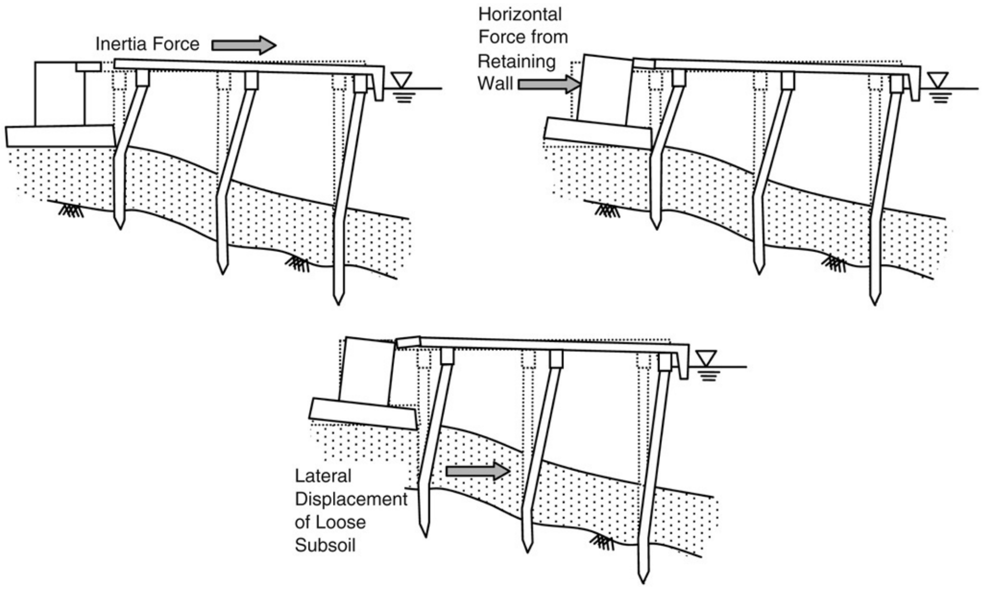

Fig. 4. Failure modes of pile supported jetty.

earthquake, high compressive stresses build up after the initial gap is closed due to the out-of-phase horizontal vibrations of the two segments of wharf. This phenomenon is called pounding and it occurs when sufficient spacing is not provided to accommodate lateral displacements during an earthquake.

Pounding was the most common cause of damage to jetties in Andaman Islands in the 2004 Sumatra earthquake. Such damage was observed between two portions of the berthing jetties at Mayabandar as well as at Diglipur Harbours and between the junctions of approach and berthing jetties at Mayabandar, Rangat, Diglipur and Sagar Dweep (Fig. 5). Similar damage was also noticed at Diglipur Harbour in the earlier 2002 M_L 6.0 Diglipur earthquake [5,6]. The observed damage and overall performance of structures demonstrate that the structures were not designed for earthquake induced lateral displacements and forces. Such damage could have been prevented or minimized by providing devices, such as restrainer, shock absorber, connector with high damping or stiffness and energy dissipation devices, or by allowing a sufficient gap at the location of movement joints of the jetties [7–10].

Fig. 5. Pounding damage to jetties in Middle Andaman, at the construction joint of approach jetty and berthing jetty at Sagar Dweep.

2.2. Damage due to short-column effect

Generally, a berthing jetty is constructed away from the shoreline inside the sea to get sufficient water depth for anchorage of the ships. It is connected to the shore by an approach jetty supported by piles, which generally are embedded in the sloping ground and therefore, have an unsupported length of piles which varies along the length of the approach jetty (Fig. 6). Piles which were largely affected in the Sumatra earthquake were those having comparatively shorter unsupported length (short piles) towards the shoreline. These comparatively stiffer short piles attract more shear forces during earthquakes than the piles with relatively longer unsupported length [11]. The lateral forces are shared among various piles proportional to their bending stiffness. For example, if a wharf is supported on two piles having same properties and if unsupported length of one pile is reduced by half, the pile will be eight times stiffer for lateral loads and as a result it will attract 78% more lateral load than the other pile (Fig. 7). Often this fact is ignored and all piles of varying lengths are assumed to carry the same amount of lateral loads. As a result, the shorter piles are easily overwhelmed by the additional lateral loads.

Therefore, slope in the natural and manmade embankment should be considered during design of piles. If short piles are not designed to withstand large amount of shear forces, they may get damaged severely during earthquakes. Such damage was observed in the piles of the approach jetty at Mayabandar where the approach slab fell from the ends due to damage to the short piles (Fig. 6), while little or no damage was observed in the relatively longer piles.

2.3. Damage due to improper design and poor maintenance

Jetty structures are continuously in contact with severe coastal environment leading to their gradual deterioration due

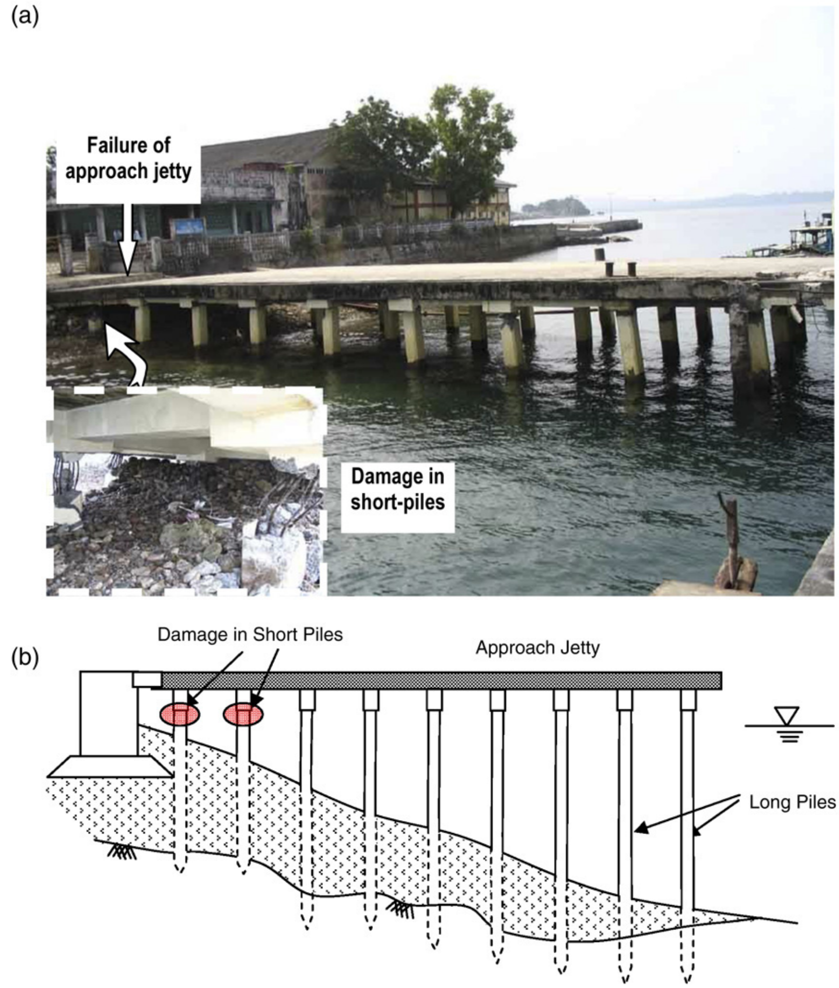

Fig. 6. (a) Damage in short-piles of the approach jetty at Mayabandar Harbour in Middle Andaman Islands, (b) Schematic diagram of the approach jetty.

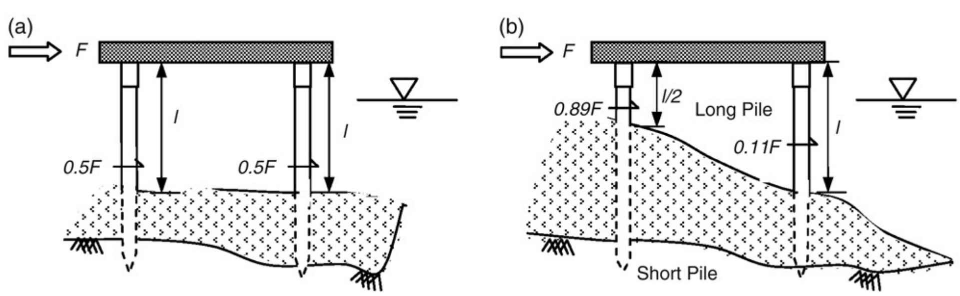

Fig. 7. Schematic of short-pile effect in jetty (a) Design condition (b) Service condition.

to electro-chemical reaction, chemical reaction, weathering, abrasion, scour, etc. Ingress of saline water and ocean spray corrode the reinforcement of the concrete structures if sufficient cover of reinforcement is not provided. Corrosion of the reinforcement will lead to the spalling of cover concrete exposing the reinforcement of piles and deck slabs. Corrosion of the exposed reinforcement may weaken the piles which led to severe damage to these piles during an earthquake. At Rangat Bay Jetty, corrosion of pile reinforcement was so severe that the transverse ties in some piles practically disappeared which caused severe damage to these piles during the Sumatra earthquake (Fig. 8). Proper care and periodical maintenance is necessary for their better performance during an earthquake.

In a marine environment, control of cracking of reinforced concrete is necessary to prevent ingress of water and oxygen which help corrosion of the reinforcing steel. Allowable crack width should be less than 0.25 mm to minimize deterioration of the reinforcement [12]. Typically, the corrosion rate is less pronounced in embedded and submerged portion of the pile where the oxygen content is less. On the other hand, the rate of corrosion in reinforcement is more where the pile is free standing out of water or in the splash zone where

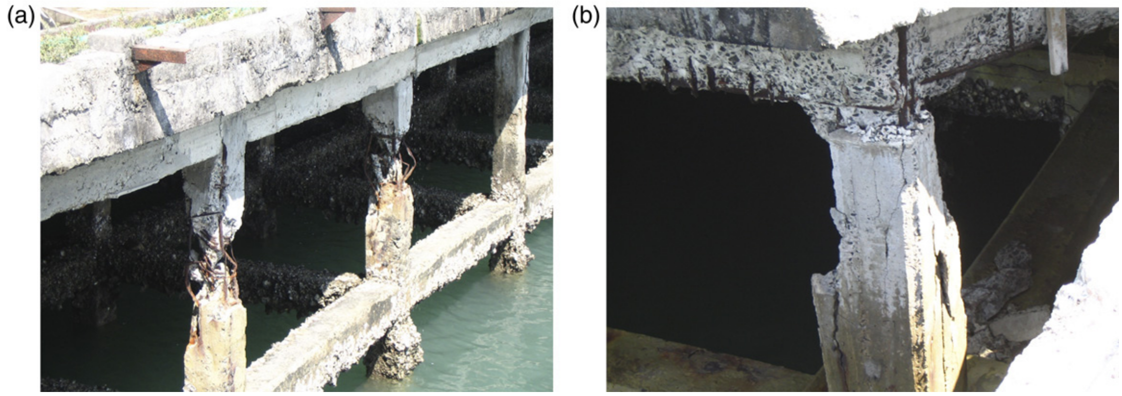

Fig. 8. Rangat Bay Harbour at Middle Andaman: (a) Severe corrosion led to damage of columns of approach jetty during the earthquake, (b) Damaged beams and piles.

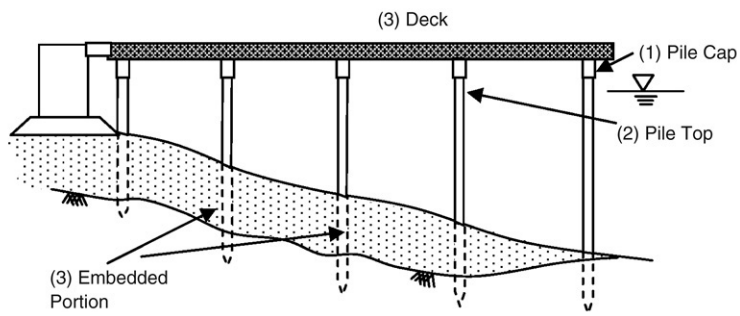

Fig. 9. Preferred sequence for yielding of pile supported jetty depending on ease of restoration.

periodical wetting and drying take place. Galvanized or plastic-coated reinforcing bar should be used to prevent corrosion of the reinforcement. Alkali-aggregate reaction also deteriorates concrete structures. It can be prevented by restricting the alkali content of the cement to 0.6% [12,13].

Inadequate shear reinforcement, improper detailing at the pile head and beam connections may be the cause of poor performance in some harbour structures. End anchorage should be such that proper force transfer takes place at the pile–deck joint. The joint should be properly confined with spiral or hoop confinement. Due to this inadequate detailing of transverse reinforcement, shear failure occurs at the top of the piles of approach jetty. Similar damage were observed in 2002 Diglipur earthquake [5,6] and the crushed concrete was replaced with microconcrete and no assessment was made of the ability of the structure to resist strong earthquake shaking in future.

A part of the berthing jetty at Diglipur Harbour sunk due to pile failure underneath. Failure of piles over the portion embedded in the soil is not desirable since it is difficult to restore. With respect to the ease of restoration and repair, the preferred sequence for yielding of a pile-supported wharf is pile cap, pile top and deck and embedded portion of the pile (Fig. 9). The connection between the wharf deck and retaining wall should be such that it can safely withstand displacement from the retaining wall and it should also be easily repairable.

3. Damage to other harbour structures

Apart from jetties or wharves, harbour structure consists of a breakwater, slipway, port control tower (PCT), passenger terminal hall, beacon light tower, etc. All these structures were damaged during the 2004 Sumatra Earthquake. Passenger terminal hall building in Haddo wharf at Port Blair was due to excessive settlement/failure of piles [14]. Out-of plane failure of hallow block masonry infill was found in passenger terminal building at Mayabandar. Some noticeable damage was found in breakwater at Rangat bay and slipway at Mayabandar harbour. These damage was mainly due to slope-stability failure and liquefaction of soils.

3.1. Slope-stability failure

Stability against lateral forces, e.g., sea waves, earthquake loading, etc. is maintained by shear resistance of the soil or rubble, resistance to overturning and bearing capacity failure. Stability of slope is commonly evaluated by pseudostatic, sliding block or stress–deformation analyses [15]. Initiation of slope stability failure occurred in the form of longitudinal cracks at the centre of the rubble mound portion of breakwater at Rangat (Fig. 10). Typical failure mode of such breakwaters is settlement due to foundation deformation beneath the rubble mound [12].

3.2. Damage due to liquefaction of soil

The poor performance of many ports during the past earthquakes around the world was primarily due to liquefaction of soil [16]. Evidence of liquefaction and sand boil was noted at Mohanpur, Diglipur and Mayabandar in the Andaman Islands

(a)

(b)

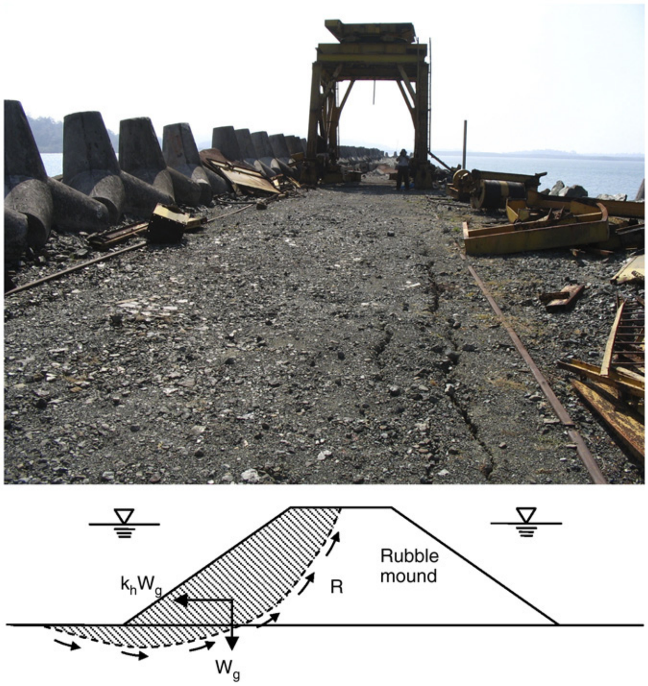

Fig. 10. (a) Longitudinal cracks on the top of the breakwater at Rangat Bay Harbour at Middle Andaman (b) Schematic diagram for pseudostatic analysis of a breakwater.

during the 2004 Sumatra earthquake [14]. Excessive ground deformation caused severe damage to the Post Office nearby Mayabandar Harbour. The approach pavement and seawall around the slipway at Mayabandar Harbour were severely damaged by liquefaction of soil (Fig. 11).

Assessment for liquefaction potential is necessary for harbour structures. The liquefaction potential of sandy soil can be evaluated based on standard penetration test (SPT) or cone penetration test (CPT) using empirical criteria [15,17]. Many well-established remedial methods can be used to reduce the susceptibility of soil liquefaction, e.g. compaction of sandy soil, installation of gravel columns, lowering the ground water table, etc. Installation of long piles is very effective especially for jetties or wharves since such piles are placed into denser soil at depth so that the liquefaction of the intermediate layer does not affect the structure.

4. Code provisions

There are few codes and guidelines for the seismic design of various ports around the world [18–22]. Comparison of seismic design strategies of different codes and guidelines are discussed in the report of PIANC [12]. Currently, two-level approach is applicable to design of harbour structures. In Level 1 design, operating level earthquake (OLE) is considered which has a 50% probability of exceedance in 50 years which is roughly 72 years of average return period. Operation of ports should not be interrupted under this level of earthquake shaking. All damage that occurs should be easily detectable and accessible for inspection and repair. Level 2 or contingency level earthquake (CLE) motions (10% probability of exceedance in 50 years or 475 years of average return period), should be resisted by jetties, retaining structures/dykes and critical operational structures so as to prevent major structural damage and collapse. Location of damage should be such that it is visually observable and easily accessible for repairs, e.g. damage to foundation elements below ground level is not acceptable. Under this level of shaking, collapse of wharf or jetty must be prevented. However, controlled plastic deformation is considered acceptable if it is economically

(a)

(b)

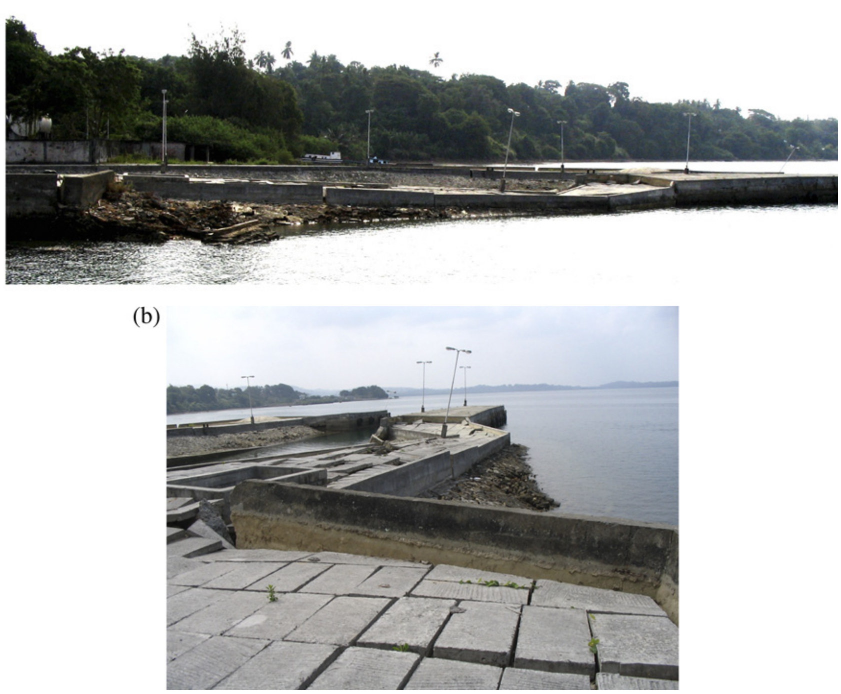

Fig. 11. (a) Liquefaction of underlying soil in the slipway at Mayabandar Harbour in Middle Andaman Islands (b) Enlarged view of the damaged slipway.

repairable within an acceptable period of time and is not a threat to life safety. Container cranes and any other critical components should be operational with only minor repairs.

Analysis methods available for port structures can be classified as simplified analysis, simplified dynamic analysis and dynamic analysis. In simplified analysis, the pile–deck system of pile-supported wharves/jetties or frames of cranes, are modelled by single degree of freedom (SDOF) or multidegree of freedom (MDOF) system. The earthquake motions are generally represented by the response spectrum method [11]. In simplified dynamic analysis, pushover analysis is performed by modelling the pile supported wharves or cranes as SDOF/MDOF system for evaluating ductility factor/strain limit. Soil-structure interaction (SSI) effects are not considered in the analysis. Displacement, ductility factor, location of plastic hinge, buckling in the structures can be obtained from such analysis. In dynamic analysis, SSI is considered using finite element method or finite difference method [12].

Performance of pile-supported jetty or wharf depends on the design and detailing of piles and pile–deck connections. Pile-deck connection is designed such that the moment can transferred from deck to pile. Piles in sloping ground should be considered for the short-column effect. During an earthquake, a plastic hinge should form above the sea bed preferably at the pile head. Displacement capacity of pile hinges controls the inelastic response of wharves or jetties to seismic excitation. Confinement should be taken into account for the designed of piles since confinement increases the pile capacity. Special confining reinforcement in forms of spiral or hoop reinforcement should be provided for at least twice the diameter of piles at the plastic hinge locations. Shear strength calculation of piles should consider not only the effect of shear strength of concrete and transverse reinforcement but also the effect of axial load. Proper seismic provision should be made for retrofitting and strengthening of old existing construction for better performance in future earthquakes.

5. Conclusions

Several wharves and jetties were damaged in the 26 December 2004 Sumatra earthquake in Andaman Islands (north of Port Blair) located about 1000 km north-west of the epicentre of the earthquake. This damage to critical transportation facilities underline the extreme vulnerability of port structures in the region. Two most common causes of damage was the pounding between the two portions of deck slabs of jetties and short-column effect in piles supporting them. In some cases, liquefaction of soil and slope-stability failure were also responsible for damage to harbour structures. Inadequate shear design of piles, improper detailing, (mainly inadequate lapping of longitudinal bars) and inadequate anchorage length resulted in damage to several piles under the wharves. Apart from the offshore structures, there were damages to different foreshore structures related to the harbour, i.e. breakwater, spill way, passenger hall building, etc. The performance of harbour structures in A&N Islands underlines the need to use seismic provisions for the design of harbour structures in seismically active regions and emphasizes the need for developing techniques to upgrade existing deficient structures in order to keep them functional during future earthquakes.

Acknowledgements

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